

MINIMAL SUGRA MODEL AND COLLIDER SIGNALS

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The SUSY signals in the dominant stau-neutralino coannihilation region at a 500(800) GeV linear collider are investigated. The region is consistent with the WMAP measurement of the cold dark matter relic density as well as all other current experimental bounds within the mSUGRA framework. The signals are characterized by an existence of very low-energy tau leptons in the final state due to small mass difference between $\tilde{\tau}_1$ and $\tilde{\chi}_1^0$ (5-15 GeV). We study the accuracy of the mass difference measurement with a 1° active mask to reduce a huge SM two-photon background.

1 Introduction

The recent measurement of cold dark matter (CDM) relic density from WMAP¹ along with the Higgs mass bound and the $b \rightarrow s\gamma$ constraint have restricted the parameter space significantly² within the framework of minimal supergravity (mSUGRA) model.^{3,4} One prominent parameter space is the region where the mass difference (ΔM) between the lighter stau ($\tilde{\tau}_1$) and the lightest neutralino ($\tilde{\chi}_1^0$) is about 5-15 GeV. This small mass difference allowed the $\tilde{\tau}_1$ to coannihilate in the early universe along with the $\tilde{\chi}_1^0$ in order to produce the current amount of the CDM ($\tilde{\chi}_1^0$). The coannihilation region has a large extension for $m_{1/2}$ up to 1-1.5 TeV, and can be explored at the LHC. The main difficulty, however, in probing this region is to detect very low-energy taus in the final state of the SUSY events due to the small ΔM value.

In this paper, we report a feasibility study of measuring the small mass difference in this $\tilde{\tau}_1$ - $\tilde{\chi}_1^0$ coannihilation region at a 500 GeV linear collider (LC).

2 mSUGRA Parameter Space

The mSUGRA model depends on only four parameters and one sign. These are m_0 (the universal soft breaking mass at the GUT scale M_G); $m_{1/2}$ (the universal gaugino soft breaking mass at M_G); A_0 (the universal cubic soft breaking mass at M_G); $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$ at

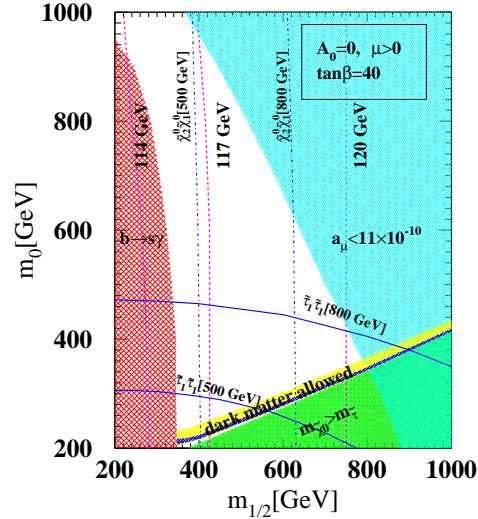


Figure 1. Allowed region in the m_0 - $m_{1/2}$ plane from the relic density constraint for $\tan\beta = 40$, $A_0 = 0$ and $\mu > 0$. The details are provided in text.

the electroweak scale; and the sign of μ , the Higgs mixing parameter in the superpotential ($W_\mu = \mu H_1 H_2$).

Figure 1 is an example of the allowed region in the m_0 - $m_{1/2}$ plane for $\tan\beta = 40$ with $A_0 = 0$ and $\mu > 0$. The most important experimental results for limiting the parameter space are: (1) The light Higgs mass bound (pink lines in the figure) from LEP:⁵ $M_h > 114$ GeV; (2) The $b \rightarrow s + \gamma$ branching ratio (brick red region):⁶ $2 \times 10^{-4} < \mathcal{B}(B \rightarrow X_s \gamma) < 4.5 \times 10^{-4}$; (3) Previous CDM ($\tilde{\chi}_1^0$) density bounds of $0.07 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.21$ (yellow band) from balloon flights (Boomerang,

Maxima, Dasi, etc.) and the 2σ bound of $0.095 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$ (blue band) from WMAP¹; (4) The bound on the lightest chargino mass:⁷ $\tilde{\chi}_1^\pm > 104$ GeV; (5) Possible muon magnetic moment anomaly (light blue region to be excluded if $\delta a_\mu > 11 \times 10^{-10}$).⁸

It is striking to learn that only two SUSY production processes can be studied at a 500 GeV LC: $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$. The kinematical reaches via the $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production are also shown in Fig. 1. The maximum reach in $m_{1/2}$ along the coannihilation band can be expected via $e^+ e^- \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- \rightarrow (\tau^+ \tilde{\chi}_1^0) + (\tau^- \tilde{\chi}_1^0)$.

We use the hadronic final state of tau (τ_h) since it has larger branching ratios. Due to the small ΔM value, the taus in the final states are low energy and hence harder to detect.

3 SUSY Signals at 500 GeV LC

In order to optimize the event selection cuts, we choose three points of $m_0 = 205, 210$ and 220 GeV for $m_{1/2} = 360$ GeV, $\tan \beta = 40$, $\mu > 0$, and $A_0 = 0$. The SUSY masses given by ISAJET⁹ are summarized in Table 1. There are two major Standard Model (SM) background processes: (i) four-fermion final state $\bar{\nu} \nu \tau^+ \tau^-$ arising from processes such as diboson (WW, ZZ) production, and (ii) two-photon processes $e^+ e^- \rightarrow \gamma^* \gamma^* + e^+ e^- \rightarrow \tau^+ \tau^-$ (or $q\bar{q}$) + $e^+ e^-$ where the final state $e^+ e^-$ pair are at a small angle to the beam pipe and the $q\bar{q}$ jets fake a $\tau^+ \tau^-$ pair.

The production cross-sections for SUSY (ISAJET) and SM four-fermion processes (WPHACT¹⁰) are listed in Table 2 for a 500 GeV LC. We choose with right handed (RH) polarized electron beams to enhance the $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ events over the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ and SM four-fermion events.

In Table 3, we summarize the event selection criteria for the RH case. The Monte Carlo (MC) events are generated, simulated and analyzed using the following programs:

Table 1. Masses (in GeV) of SUSY particles in three representative scenarios of ΔM for $m_{1/2} = 360$ GeV, $\tan \beta = 40$, $\mu > 0$, and $A_0 = 0$.

MC Pt.	m_0	$M_{\tilde{\chi}_2^0}$	$M_{\tilde{\tau}_1}$	$M_{\tilde{\chi}_1^0}$	ΔM
1	205	274.2	147.2	142.5	4.7
2	210	274.2	152.0	142.5	9.5
3	220	274.3	161.6	142.6	19.0

Table 2. SUSY and SM production cross sections ($\sigma \cdot B(\tau \rightarrow \tau_h)^2$ in fb) for polarization for electron beams of $\mathcal{P}(e^-) = -0.9(\text{RH})$.

SUSY Pt. 1.	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	0.43
	$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	28.25
SUSY Pt. 2.	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	0.39
	$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	25.85
SUSY Pt. 3.	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	0.38
	$\tilde{\tau}_1^+ \tilde{\tau}_1^-$	22.95
SM (four fermion process)		7.84

ISAJET⁹ to generate SUSY events; WPHACT¹⁰ for SM backgrounds; TAUOLA¹¹ for tau decay; a LC detector simulation² to reconstruct jets with JADE algorithm.¹² In our calculation, beamstrahlung and bremsstrahlung are included in both ISAJET and WPHACT.

The accepted number of signal and background events are summarized in Tables 4 and 5. It should be noted that the number of SM $\gamma\gamma$ events with the forward electrons just below 3° are 11400. The acceptances for $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ events are 11.2%, 5.9%, and 0.86% for $\Delta M = 19, 9.5$, and 4.7 GeV, respectively with 1° mask. The acceptance drops fast as ΔM goes below 5 GeV. For example, 0.23% for $\Delta M = 3.8$ GeV ($m_0 = 204$ GeV). We see the robust discovery significance for the signal events for $\Delta M \gtrsim 5$ GeV with 1° mask in Table 6. We conclude that the mask is essential to detect SUSY events in this region of parameter space.

Table 3. Event selection criteria for the RH ($\mathcal{P} = -0.9$) case.

Variable(s)	Cuts
$N_{jet}(E_{jet} > 3 \text{ GeV})$	2
τ_h ID	1, 3 tracks
Jet acceptance	$ \cos(\theta_{jet}) < 0.65$ $-0.6 < \cos[\theta(j_2, p_{vis})] < 0.6$
Missing $p_T(\cancel{p}_T)$	$> 5 \text{ GeV}$
Acoplanarity	$> 40^\circ$
Veto on EM clusters or electrons	No EM cluster in $5.8^\circ < \theta < 28^\circ$ with $E > 2 \text{ GeV}$ No electrons within $\theta > 28^\circ$ with $p_T > 1.5 \text{ GeV}$
Beam mask (1° (or 2°) - 5.8°)	No EM cluster with $E > 100 \text{ GeV}$

Table 4. Number of SUSY events expected with 500 fb^{-1} for the RH case.

Process	$\Delta M = 4.7$	9.5	19
$\tilde{\chi}_2^0 \tilde{\chi}_1^0$	15	26	29
$\tilde{\tau}^+ \tilde{\tau}^-$	122	786	1283

Table 6. Significance ($N_S/\sqrt{N_B}$) with 500 fb^{-1} for SUSY discovery using 1° mask.

Process (RH)	$\Delta M = 4.7$	9.5	19
$\tilde{\tau}^+ \tilde{\tau}^-$	10	63	101

Table 5. Number of SM events expected with 500 fb^{-1} .

SM four-fermion	129
SM $\gamma\gamma$ 2-5.8° Mask	248
1-5.8° Mask	2

4 Measurement of Stau Neutralino Mass Difference

Since ΔM is small, it needs to be measured with a very good accuracy. We choose the invariant mass $M_{\text{eff}} \equiv M(j_1, j_2, \cancel{E})$ of two τ -jets and missing energy as a key discriminator. We generate high statistics MC samples for the SM and various SUSY events (by changing the m_0 value) and prepare the templates of the M_{eff} distributions for the SM, $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, and $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ events.

We then generate the MC samples equivalent to 500 fb^{-1} of luminosity for particular ΔM values and fit them with the template functions. For example, in Fig. 2 we show the fitting of the 500 fb^{-1} MC samples for Point 2 with the templates for $m_0 = 210 \text{ GeV}$ and

calculate the χ^2 of the fits. Here the χ^2 value is calculated as $\chi^2 = \sum_i \left(\frac{N_i - \sum_j C_j F_i^j}{\sigma_i} \right)^2$ where N_i is the number of events in i -th M_{eff} bin of the 500 fb^{-1} sample, $C_j F_i^j$ is the corresponding value for the template “ j ” where j is for SM, $\tilde{\tau}_1^+ \tilde{\tau}_1^-$ or $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ processes. C_j is a normalization parameter and a free variable except for the SM process. This is because we should be able to measure the SM events very well before we discover SUSY events.

We scan the range of $m_0 = 203\text{--}220 \text{ GeV}$ and plot the $\Delta\chi^2 \equiv \chi^2 - \chi_{\text{min}}^2$ in Fig. 3. The $\Delta\chi^2$ value is minimum for the template for $m_0 = 210 \text{ GeV}$. We find that 1σ in the $\Delta\chi^2$ corresponds to $9.5 \pm 1 \text{ GeV}$, where the true value of ΔM for the Point 2 is 9.53 GeV.

We repeat the same study for different stau masses i.e. for different ΔM values and two different beam mask designs (1° and 2°). For $\Delta M \sim 5 \text{ GeV}$, a beam mask of 1° is crucial. The accuracy of mass determination for is summarized in Table 7, showing the uncertainties are at a level of 10%.

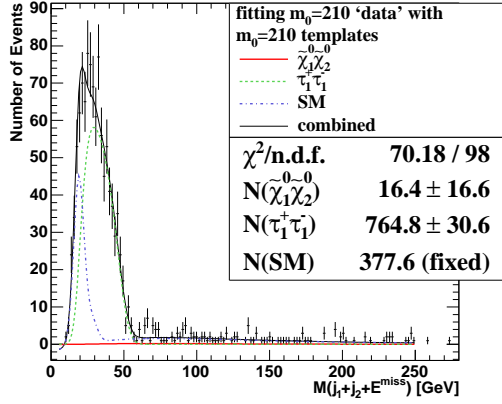


Figure 2. $M_{\text{eff}} (\equiv M(j_1, j_2, E))$ distributions for a 500 fb^{-1} MC samples for SUSY ($m_0 = 210 \text{ GeV}$) and SM events, being fitted to the templates for $m_0 = 210 \text{ GeV}$.

Table 7. Accuracy of the ΔM determination for different beam mask designs. “-” means we cannot determine with 500 fb^{-1} .

ΔM	$N_{\tilde{\tau}_1^+ \tilde{\tau}_1^-}$ (500 fb^{-1})	ΔM (“ 500 fb^{-1} ” expt.)	
		2° mask	1° mask
4.76	122	-	$4.74^{+0.97}_{-1.03}$
9.53	787	$9.5^{+1.1}_{-1.0}$	$9.5^{+1.0}_{-1.0}$
12.4	1027	$12.5^{+1.4}_{-1.4}$	$12.5^{+1.1}_{-1.4}$
14.3	1138	$14.5^{+1.1}_{-1.4}$	$14.5^{+1.1}_{-1.4}$

5 Conclusion

At 500 GeV LC, it is crucial to instrument an active mask to detect very forward electrons down to 1° for measurement of the small ΔM . The expected accuracy is 10% (20% for $\Delta M \sim 5 \text{ GeV}$) with 500 fb^{-1} .

Acknowledgments

This work is supported in part by a NSF Grant PHY-0101015, in part by NSERC of Canada and in part by a DOE Grant DE-FG02-95ER40917.

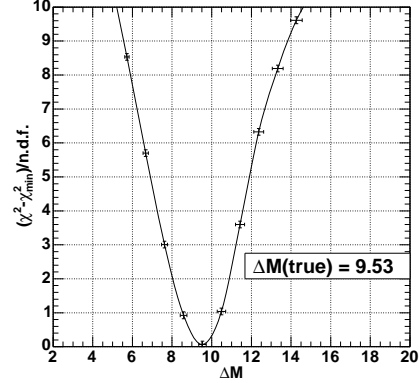


Figure 3. χ^2 (defined in the text) for Point 2 as a function of ΔM .

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